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A Brief Review of the Study of Unstable States in the Dissociation of Relativistic Nuclei

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Abstract—The article presents a review of the results of studies of the unstable states in the relativistic dissociation of nuclei ^{10}B, ^{11,12}C, ^{16}O, ^{22}Ne, ^{28}Si, ^{84}Kr, and ^{197}Au in the energy range from hundreds of MeV/nucleon to several tens of GeV/nucleon using the nuclear track method. A systematic study of the fragmentation of incident nuclei with multiple production of the lightest fragments of He and H made it possible to study the dynamics of the manifestation of unstable nuclear states of ^{8}Be, the Hoyle state, and the 4α-particle state of the ^{16}O nucleus above the threshold in the relativistic dissociation of nuclei thanks to precision measurements of fragment outgoing angles. It is shown that, to reconstruct the relativistic decays of unstable nuclei in a nuclear photographic emulsion, it is sufficient to determine the invariant mass of the system of He and H fragments in the approximation of conservation of momentum per nucleon of the parent nucleus. This approach makes it possible to search for more complex nuclear states. An indication was obtained of an increase in the probability of detecting ^{8}Be with an increase in the number of relativistic α particles in the event.

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INTRODUCTION

One of the key aspects of nuclear structure is the presence of degrees of freedom in which quartets of spin-paired protons and neutrons behave as constituent clusters, manifested in the intense production of α particles in a wide variety of nuclear reactions and decays. The transition to the study of ensembles of α particles immediately above the binding thresholds makes it possible to identify the role of unstable ^{8}Be and ^{9}B nuclei and the 3α Hoyle state (HS) and to search for their analogs.

The use of a technically simple and inexpensive nuclear emulsion (NE) technique in relativistic nuclear beams provides flexibility and uniformity at the search stage and, in the theoretical aspect, transparency of interpretation. It would be particularly good to demonstrate the similarity of conclusions based on relativistic invariance. During the dissociation of relativistic nuclei in a narrow fragmentation solid angle, ensembles of He and H nuclei are intensively generated (Fig. 1). Particularly valuable are the so-called "white" stars, in the region of the interaction vertex of which no tracks of the target nucleus and produced mesons are observed. In addition, when tracking in the direction of the heavy nuclei fragmentation cone, one can observe stars that do not have an incoming track from the event vertex, which arise in the interactions of relativistic neutron fragments and nuclei in the NE material [1].

According to the widths, the decays of ^{8}Be, ^{9}B, and HS occur over ranges from several thousand (^{8}Be and

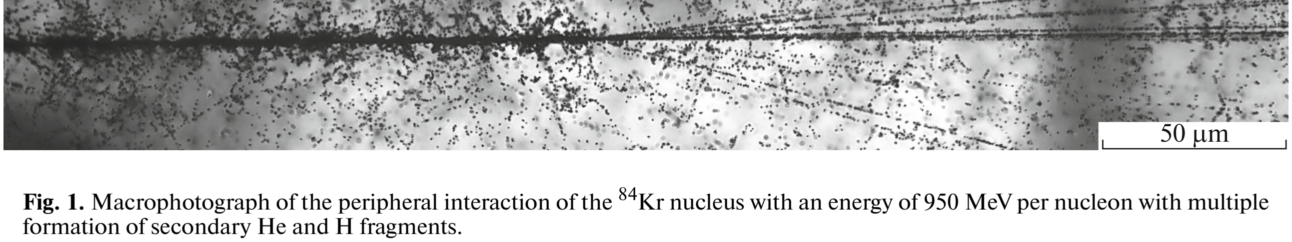

Fig. 1. Macrophotograph of the peripheral interaction of the ^{84}Kr nucleus with an energy of 950 MeV per nucleon with multiple formation of secondary He and H fragments.

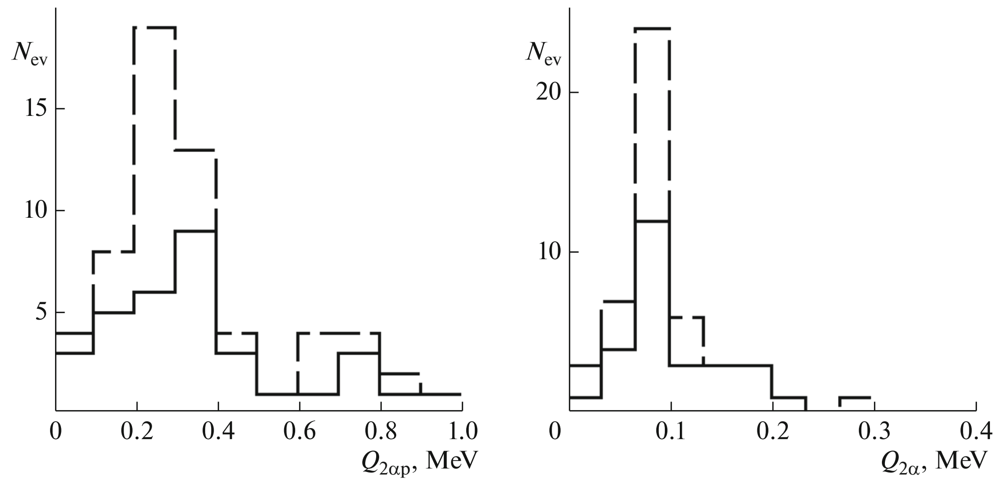

Fig. 2. Distributions of $Q_{2\alpha p}$ of $2\alpha p$ triplets by excitation energy $Q_{2\alpha p}$ for fragmentation (solid line) $^{10}B \to 2He + H$ at 1.6 A GeV/c and $^{11}C \to 2He + 2H$ at (added, dotted line) 2.0 A GeV/c and (right) of $Q_{2\alpha}$ of α pairs in ^9B decays identified in these events [7].

HS) to several tens (^9B) of atomic sizes and should be identified by a minimum invariant mass. Due to the minimum energy, the decays of ^8Be, ^9B, and HS should appear as pairs and triplets with relativistic He and H fragments with the smallest separation angles. The invariant mass of a system of relativistic fragments is defined as the sum of all scalar products of 4-momenta $\mathbf{P}_{i,k}$ of the fragments $M^{*2} = \Sigma(\mathbf{P}_i \cdot \mathbf{P}_k)$. For convenience of presentation, we introduce a variable Q defined as the difference between the invariant mass and the sum of the fragment masses $Q = M^* - \Sigma m$. The components $\mathbf{P}_{i,k}$ are determined in the approximation of conservation of initial momentum per nucleon by fragments.

Current interest in nuclear α-clustering is largely motivated by the concept of α-particle Bose–Einstein condensate (αBEC). The unstable ^8Be and HS nuclei are described as 2- and 3αBEC states, and their decays can serve as signatures of the decays of more complex nαBEC states. The existence of the latter can expand the picture of the nucleosynthesis of heavy nuclei. Recently, the statistics of dozens of ^8Be decays revealed an increase in the probability of detecting ^8Be with an increase in the number of associated α particles nα. A preliminary conclusion is drawn that the contributions from ^9B and HS decays are also increasing.

IDENTIFICATION OF DECAYS OF ^8Be AND ^9B NUCLEI IN THE DISSOCIATION OF LIGHT RELATIVISTIC NUCLEI

Analysis of the irradiation of NE layers in a beam of ^{10}B nuclei with an energy of 1A GeV made it possible to reveal the effect of dominance of the multiple fragmentation channel [2, 3]. In the distribution of fragments over the charge state, the fraction of the $^{10}B \to 2He + H$ channel was 77%. Based on measurements of the outgoing angles of He and H fragments, it was established that the unstable nucleus $^8Be_{g.s.}$ (Fig. 2, right) appears with a probability of (25 ± 5)%, of which (13 ± 3)% are due to decays of the unstable ^9B nucleus (Fig. 2, left). What is unexpected is the fact that the number of white stars $^9B + n$ is 10 times greater than $^9Be + p$. This observation may indicate a wider spatial distribution of neutrons in the ^{10}B nucleus compared to protons, resulting in a larger cross section for the $^9B + n$ channel compared to the mirror channel. In addition, with a probability of 8%, stars are observed in the $^{10}B \to {}^6Li + \alpha$ channel. It is possible that the Li nucleus, weakly manifested in the dissociation of ^{10}B, is also present in ^{10}B mainly in a “dissolved” form, giving a nonresonant contribution to the Θ_{2He} distribution [2–4].

The charge topology of the dissociation channels of the ^{11}C nuclei in NE with an energy of 1.2 A GeV has been studied. Among ^{11}C stars, events with observations of only relativistic fragments He and H, especially 2He + 2H, are dominant; their contribution was 77% [5]. A channel that is characteristic only of the ^{11}C nucleus with the formation of Li + He + H fragments has been established. Based on the measured outgoing angles of He and H fragments, in the representation of the invariant variable Q, it was shown that decays of the $^8Be_{g.s.}$ nuclei (Fig. 2, right) of all found white ^{11}C stars are represented in 21% of the $^{11}C \to 2He + 2H$ events and 19% for the 11C→3He channel. ^9B decays (Fig. 2, left) were detected in white stars $^{11}C \to 2He +$

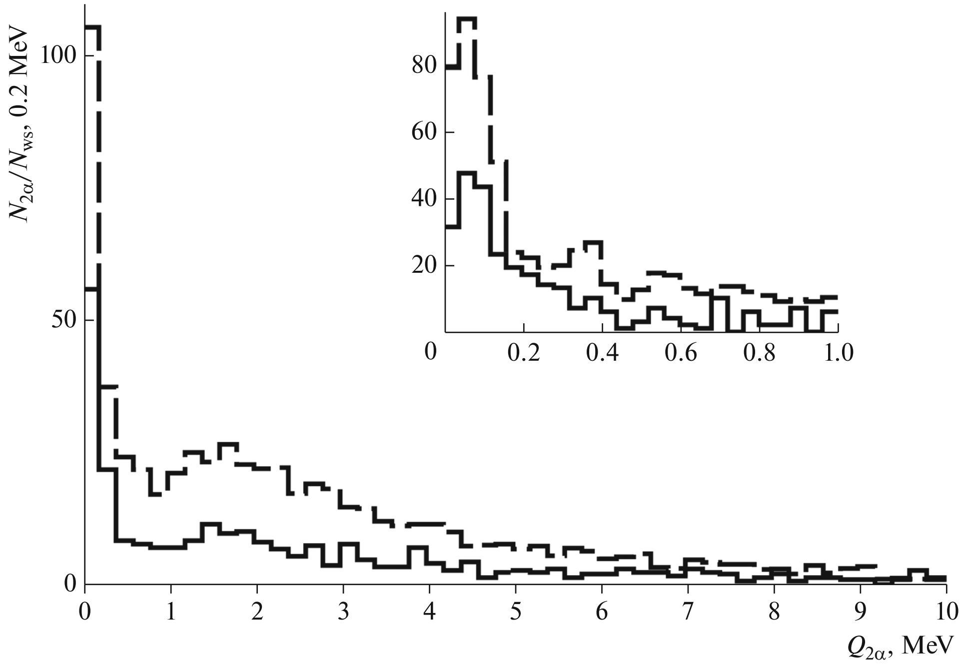

Fig. 3. Distribution of the number of 2α pairs $N_{2\alpha}$ over the excitation energy $Q_{2\alpha}$ in the coherent dissociation (solid line) $^{12}C \to 3\alpha$ and (dashed line) $^{16}O \to 4\alpha$ at 3.65 *A* GeV. (Inset) Enlarged region $Q_{2\alpha}$ < 1 MeV (step 40 keV). The histograms are normalized to the number of white stars N_{ws} [9].

2H, constituting 14% of white stars 11C → 2He + 2H. It was found that, as in the case of ^{10}C, $^8Be_{g.s.}$ decays of white ^{11}C stars almost always occur due to ^9B decays of [5, 6]. It is worth noting the lowest-energy peak in the $Q_{2\alpha 2p}$ distribution of the 18 found stars $^{11}C \to$ 2He + 2H, characterized by an average $Q_{2\alpha 2p}$ value of (2.7 ± 0.4) MeV with an rms value of 2.0 MeV [6].

The constraint established during the analysis of data on the dissociation of ^{10}B and ^{11}C nuclei on the identification of decays of ^8Be nuclei ($Q_{2\alpha}$ < 0.2 MeV) made it possible to estimate the contribution of such decays to the dissociation of relativistic nuclei $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$ in nuclear emulsion at the level of (45 ± 4)% and (62 ± 3)%, respectively (Fig. 3) [7–9].

OBSERVATION OF EVENTS WITH DECAYS OF THE HOYLE STATE

The certainty in the identification of ^8Be and ^9B became the basis for the search for HS decays in the $^{12}C \to 3\alpha$ dissociation (Fig. 4), where the limit on the *Q* variable of α triples to 0.7 MeV was established [7]. A comprehensive analysis of the $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$ stars made it possible to establish that the fraction of events containing HS decays is (11 ± 3)% for ^{12}C and (22 ± 2)% for ^{16}O (Fig. 4) [7–11]; 33 $^{16}O \to 2^8Be$ events have been identified, accounting for 5 ± 1% of the $^{16}O \to 4\alpha$ white stars. The *Q* distribution of a system of 4α particles in the $^{16}O \to 2^8Be$ events [12] indicates two candidates $^{16}O(0^+_6) \to 2^8Be$ in the region *Q* < 1.0 MeV. The dissociation statistics for the $^{16}O \to 2^8Be$ and $^{16}O \to \alpha$HS channels have the ratio (0.22 ± 0.02) [9].

It should be noted that, with an increase in 2α- and 3α-combinations in the event, the manifestation of unstable ^8Be and HS increases. Thus, HS identified in the relativistic dissociation of ^{12}C also appears in the case of ^{16}O. This result shows that HS does not reduce to the usual excitation of the ^{12}C nucleus, but, like ^8Be, is a more universal object of a nuclear-molecular nature. The closest confirmation of this assumption can be the observations of HS in the relativistic fragmentation $^{14}N \to 3\alpha$ [13]. Nevertheless, such an observation deserves verification for heavier nuclei, where α combinatorics increases rapidly with mass number.

ALPHA-PARTICLE DISSOCIATION OF HEAVY RELATIVISTIC NUCLEI

Having been assessed in the study of light nuclei, a similar search was applied to the study of dissociation events of medium and heavy nuclei to identify ^8Be and HS and search for more complex *n*αBEC states. The

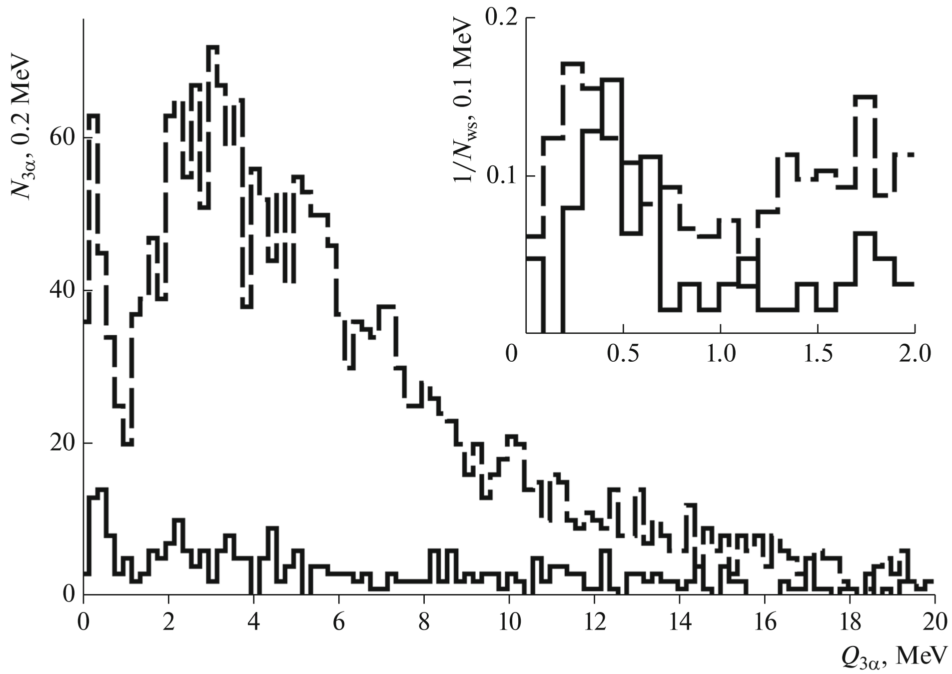

Fig. 4. Distribution of the number of 3α triples $N_{3\alpha}$ over excitation energy $Q_{3\alpha}$ for (solid lines) 316 white stars $^{12}C \rightarrow 3\alpha$ and (dashed lines) 641 white stars $^{16}O \rightarrow 4\alpha$ at an energy of 3.65 *A* GeV. (Inset) Enlarged part $Q_{3\alpha} < 2$ MeV, normalized to the number of white stars N_{ws} [9].

analysis made it possible to trace the contribution of unstable states with a higher multiplicity of He and H fragments using the method of transverse scanning of NE layers. Starting with the fragmentation of ^{16}O nuclei in the energy range 3.65–200 GeV/nucleon, the analysis showed a relative increase in the contribution of ^{8}Be nuclei with an increase in the number of relativistic α particles per event [14]. The results of measurements of 4301 interactions of ^{22}Ne nuclei at an energy of 3.22 *A* GeV have been analyzed [15]. This data set includes precision measurements of the outgoing angles of 2 to 5 relativistic α particles, which allowed analysis in the $Q_{(2-5)\alpha}$ variables. It has been established that the probability of identifying ^{8}Be, ^{9}B, and HS increases with the multiplicity of α particles in the event [15]. A similar result was obtained by analyzing 1093 events of $n\alpha$ fragmentation of ^{28}Si nuclei with an energy of 14.6 GeV/nucleon in a nuclear emulsion up to 6 α particles in the event [14]. The distribution of events with identified ^{8}Be nuclei by the $Q_{3\alpha}$ variable for the data set on ^{12}C, ^{22}N, and ^{28}S nuclei is shown in Fig. 5.

Also, the $n\alpha$ events were studied during transverse scanning of NE layers longitudinally irradiated in a beam of ^{84}Kr nuclei with an energy of 950 MeV/nucleon [12, 16]. In this analysis, the fragment momentum was corrected for the ionization loss in nuclear emulsion and multiplied by 0.8 to approximately calculate the drop in the initial momentum value upon interaction [16]. Being inessential for the selection of $Q_{2\alpha}(^{8}Be) \leq 0.4$ MeV, it further allows one to maintain the selection condition $Q_{3\alpha}(HS) < 0.7$ MeV, focusing on the $Q_{3\alpha}(HS)$ peak (Fig. 6). The $Q_{4\alpha}$ distributions up to 10 MeV indicate an α quartet at $n\alpha = 6$ with an isolated value of $Q_{4\alpha} = 0.6$ MeV, corresponding to both the αHS and $2^{8}Be$ variants [12]. Without contradicting the $^{16}O(0^{+}{}_{6})$ decay, this single observation serves as the starting point for further accumulation of statistics on the problem of the 4αBEC state.

Wide coverage of $n\alpha$ is provided by measurements of 1316 inelastic interactions of ^{197}Au at 10.7 GeV/nucleon [14]. The proportion of events with $n\alpha > 3$ among those measured was 16%. Due to the increasing complexity of measurements, the selection condition for $Q_{2\alpha}(^{8}Be)$ was relaxed to ≤ 0.4 MeV. It turned out that the ratio of the number of $N_{n\alpha}(^{8}Be)$ events with at least one identified ^{8}Be decay to their number $N_{n\alpha}$ demonstrates a strong increase with $n\alpha$ [14, 17]. In general, the correlation picture of the dependence of the multiplicity of α particles in an event and on the number of events with identified ^{8}Be decays (at least one) is shown in Fig. 7.

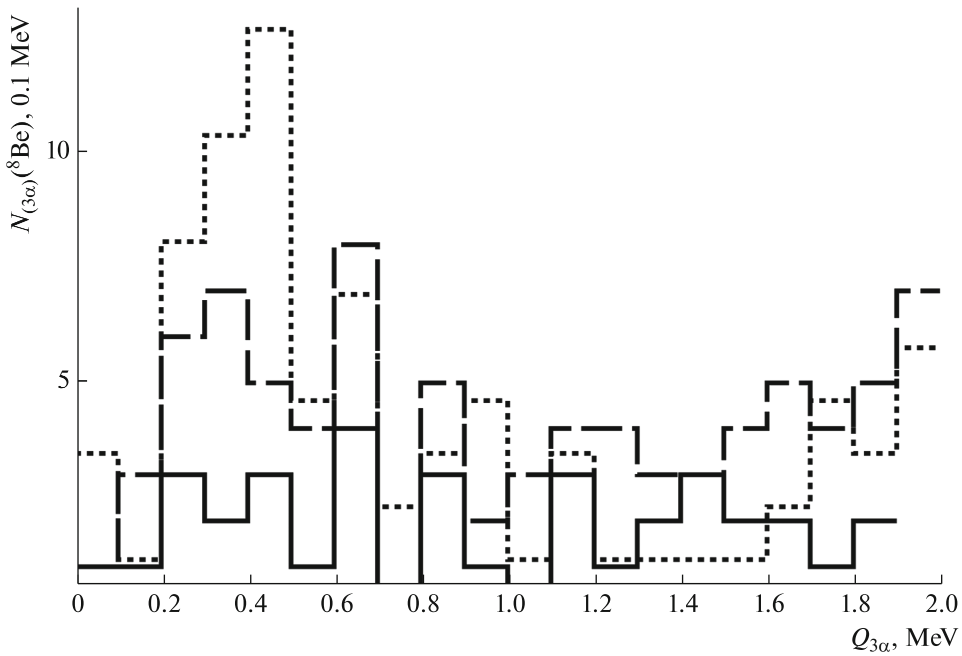

Fig. 5. Distributions of 3α systems with identified ^{8}Be $N_{(3\alpha)}(^8Be)$ decays over excitation energy $Q_{3\alpha}$ (≤2 MeV) in events of fragmentation of (solid line) ^{22}Ne nuclei with an energy of 3.22 GeV/nucleon and (dashed line) ^{28}Si nuclei with an energy of 14.6 GeV/nucleon; (dots) the distribution of $N_{(3\alpha)}(^8Be)$ in the 12C → 3α dissociation, normalized to the statistics for ^{22}Ne and ^{28}Si [14].

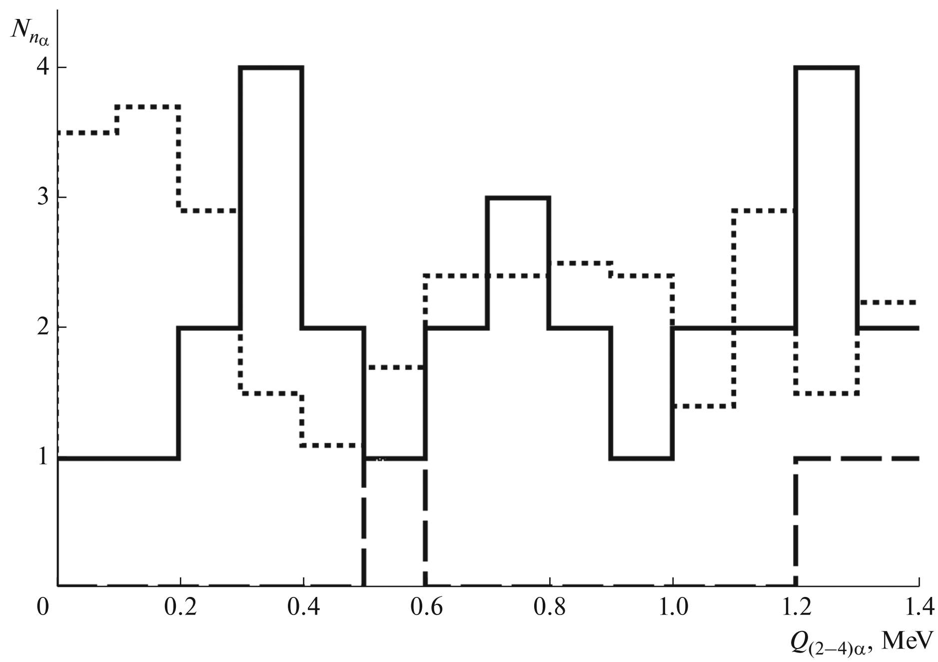

Fig. 6. Distribution in the region of low excitation energies of *n*α-systems *Q* of (dots, factor 0.1) pairs, (solid line) triplets, and (shaded) quadruples of α particles formed in the fragmentation of Kr nuclei. [12].

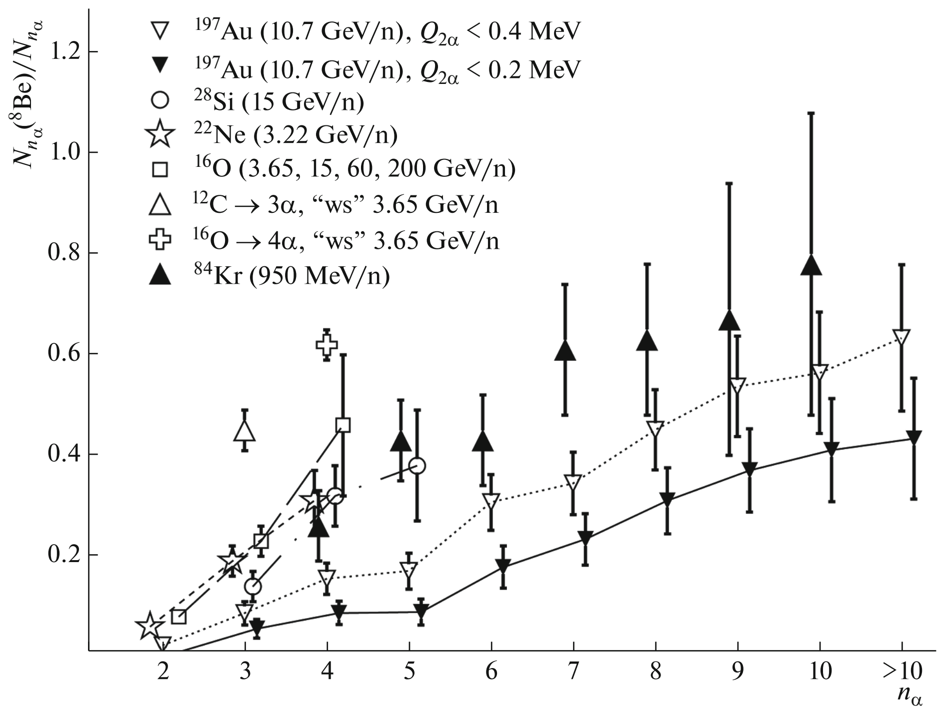

Fig. 7. Dependence of the relative contribution of decays of ^{8}Be nuclei $N_{n\alpha}(^8\text{Be})$ to the statistics of $N_{n\alpha}$ events with α-particle multiplicity $n\alpha$ in the relativistic fragmentation of C, O, Ne, Si, and Au nuclei; white stars $^{12}\text{C} \to 3\alpha$ and $^{16}\text{O} \to 4\alpha$ (WS) are marked; for convenience, the points are slightly shifted around the $n\alpha$ values and connected by lines.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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